Failure Mechanisms and Life Prediction of Thermal and Environmental Barrier Coatings under Thermal Gradients

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Ceramic thermal and environmental barrier coatings (TEBCs) will play an increasingly important role in gas turbine engines because of their ability to further raise engine temperatures. However, the issue of coating durability is of major concern under high-heat-flux conditions. In particular, the accelerated coating delamination crack growth under the engine high heat-flux conditions is not well understood. In this paper, a laser heat flux technique is used to investigate the coating delamination crack propagation under realistic temperature-stress gradients and thermal cyclic conditions. The coating delamination mechanisms are investigated under various thermal loading conditions, and are correlated with coating dynamic fatigue, sintering and interfacial adhesion test results. A coating life prediction framework may be realized by examining the crack initiation and propagation driving forces for coating failure under high-heat-flux test conditions.

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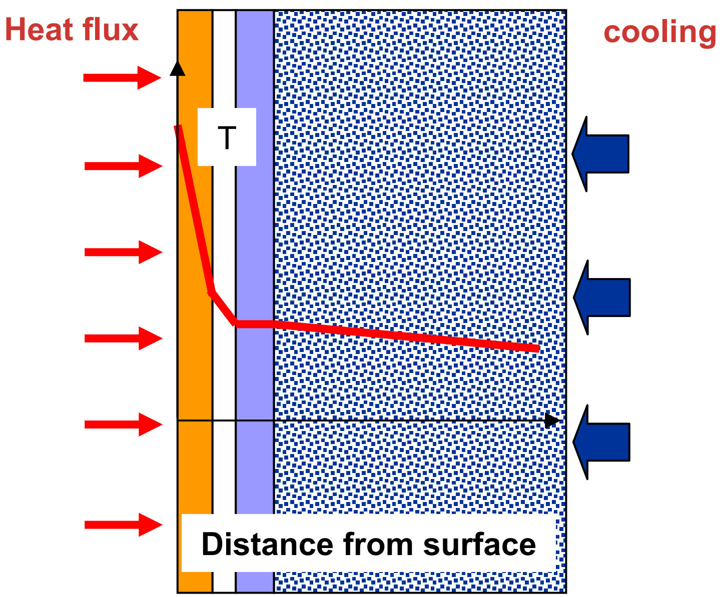
Objective

- High heat flux testing development
- The coating delamination behavior under thermal gradients
- Finite element analysis of coating delamination driving forces
- Coatings design and life prediction issues
- Summary and Conclusions

High-Heat-Flux Tests Critical to Turbine Component Coating Development

– **High-heat-flux laser test approach for thermal barrier coating cyclic durability**

- Temperature gradient requirements: up to 200 °C/100 microns
- Heat flux requirements up tp 200-300 W/cm^2

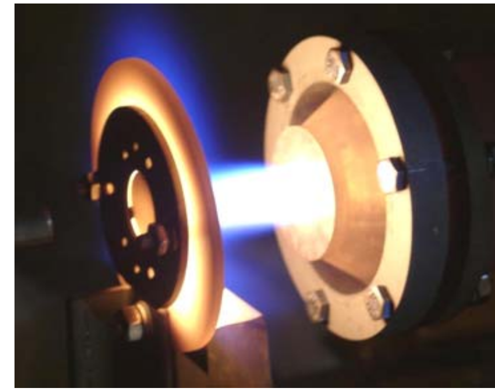


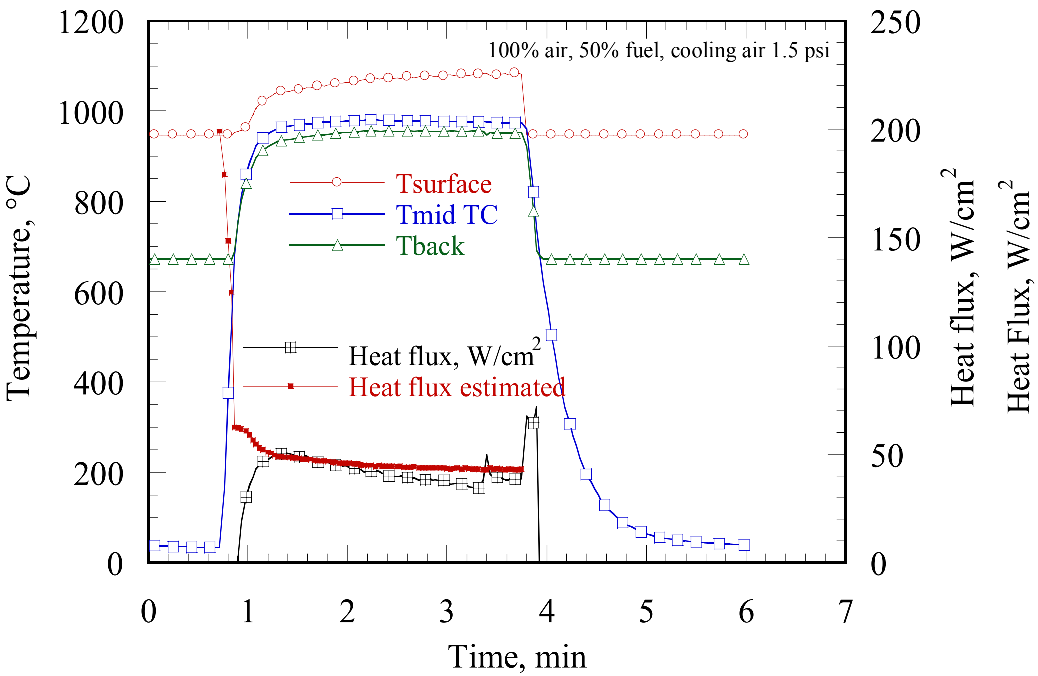
NASA CO_2 Laser Rig

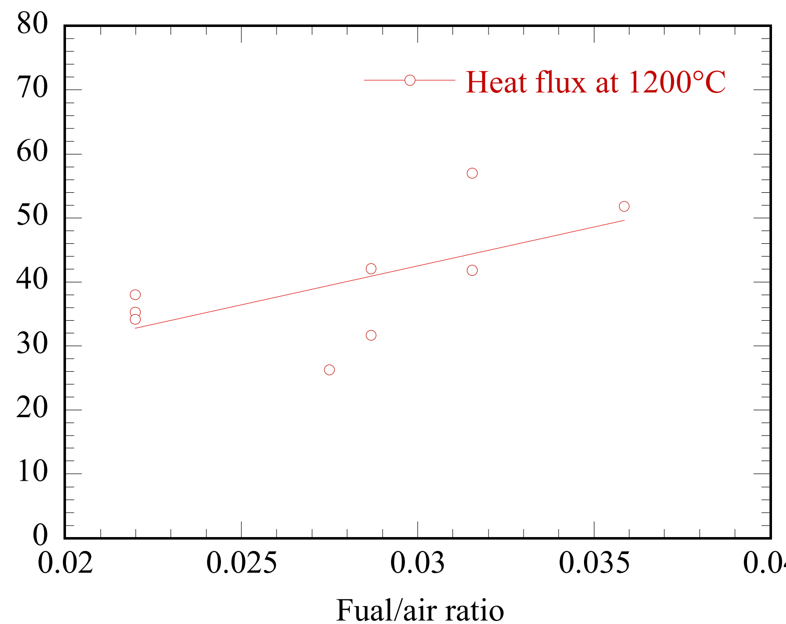
Current capability up to 315 W/cm^2

High-Heat-Flux Tests Critical to Turbine Component Coating Development (continued)

- **Atmospheric burner rig heat fluxes characterized using an embedded thermocouple (TC) sensor approach**
- **Initial heat fluxes 100-200 W/cm² observed**

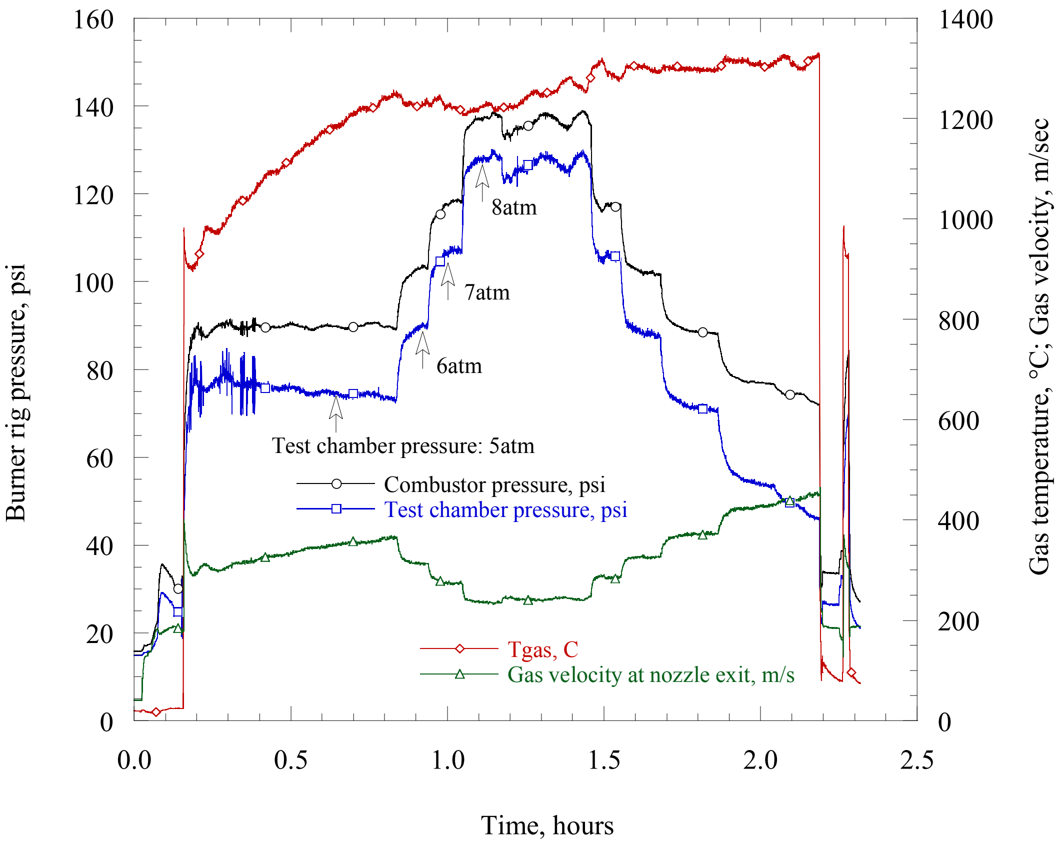


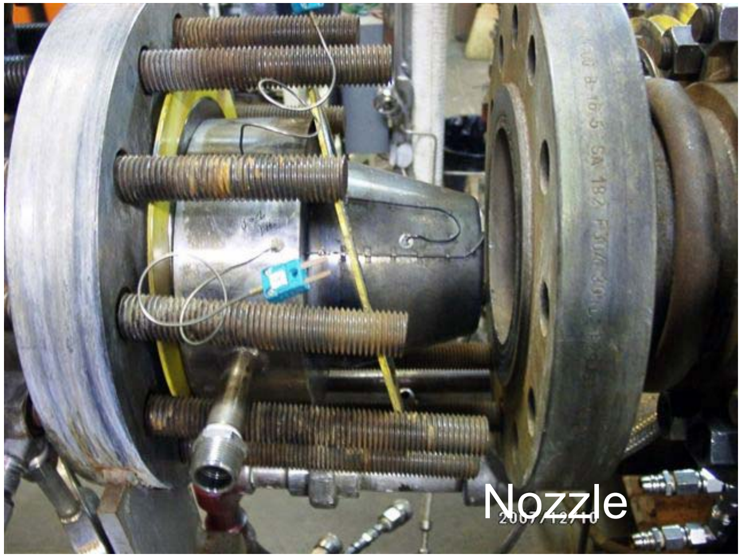


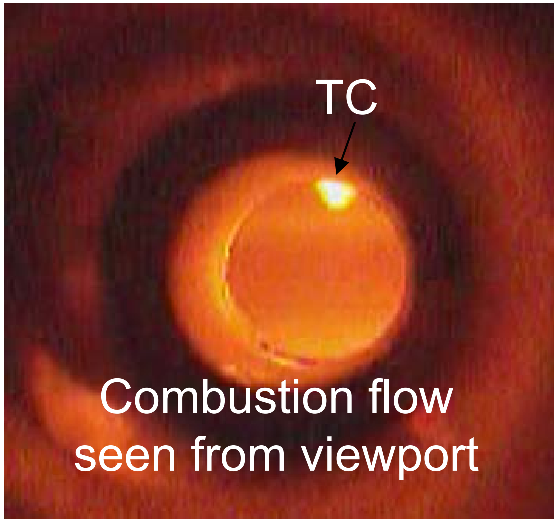


High-Heat-Flux Capability Recently Developed for High Pressure Burner Rig

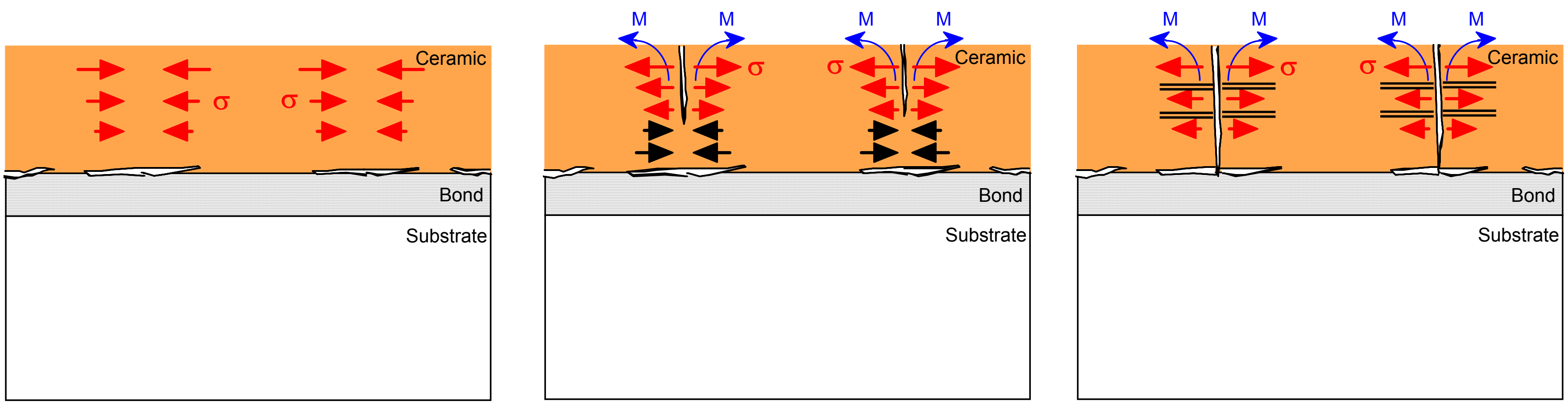
— Testing pressure up to 12 atm
— Gas velocity up to 400 m/s
—- Heat flux up to 200 W/cm²







Generalized Coating Failure Modes for Thermal Barrier Coatings under Thermal Gradients



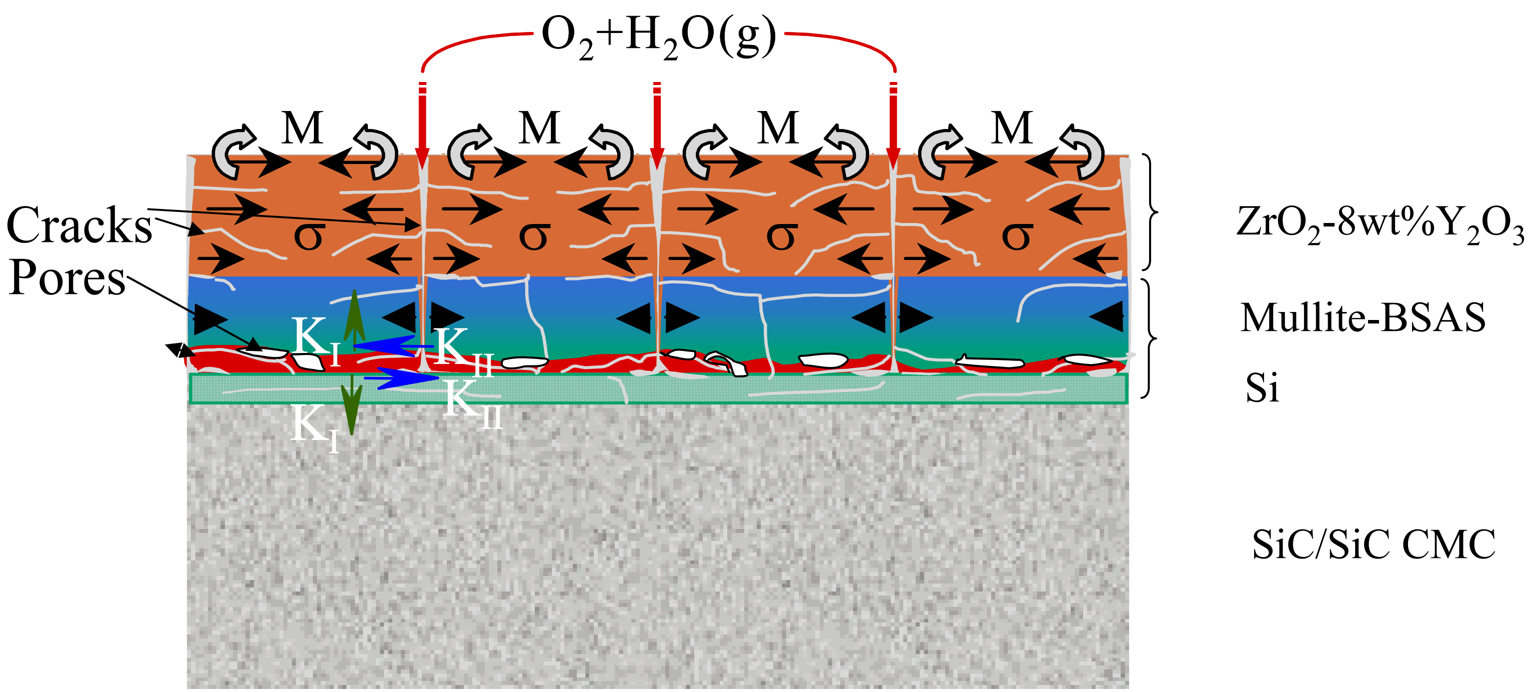
(a) Low Heat Flux and High Interface Temperature

(b) Medium Heat Flux and Interface Temperature

(c) High Heat Flux and Low Interface Temperature

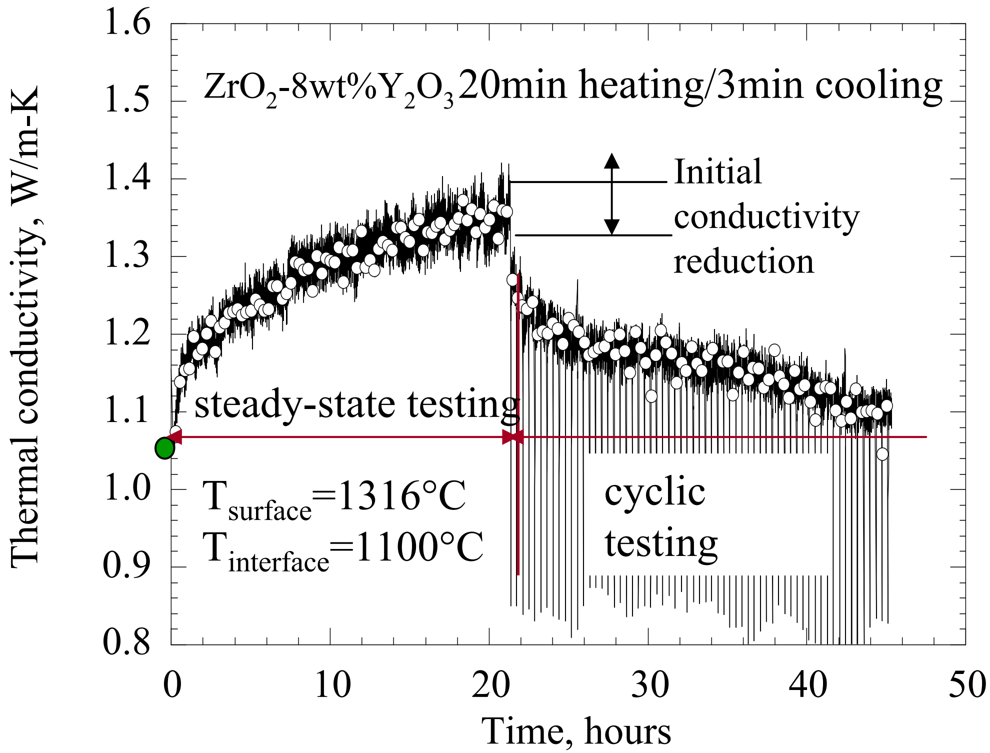
Generalized Coating Failure Modes for Environmental Barrier Coatings under Thermal Gradients

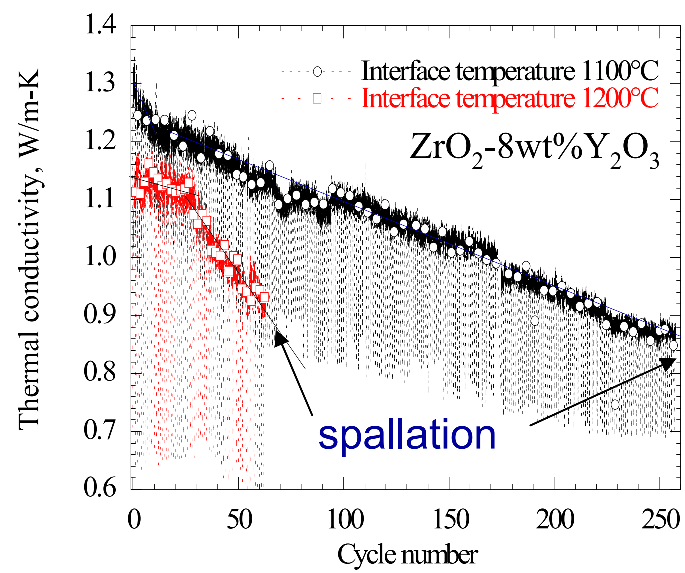
- Sintering and CTE mismatch induces surface wedge-shape crack propagation
- Surface cracking accelerates coating delamination under mixed mode loading (K_I and K_{II})
- Interfacial pore formation due to the chemical reactions further accelerated coating spallation under thermal gradient conditions



Damage Accumulation of Thermal Barrier Coatings under Laser Heat Flux Testing

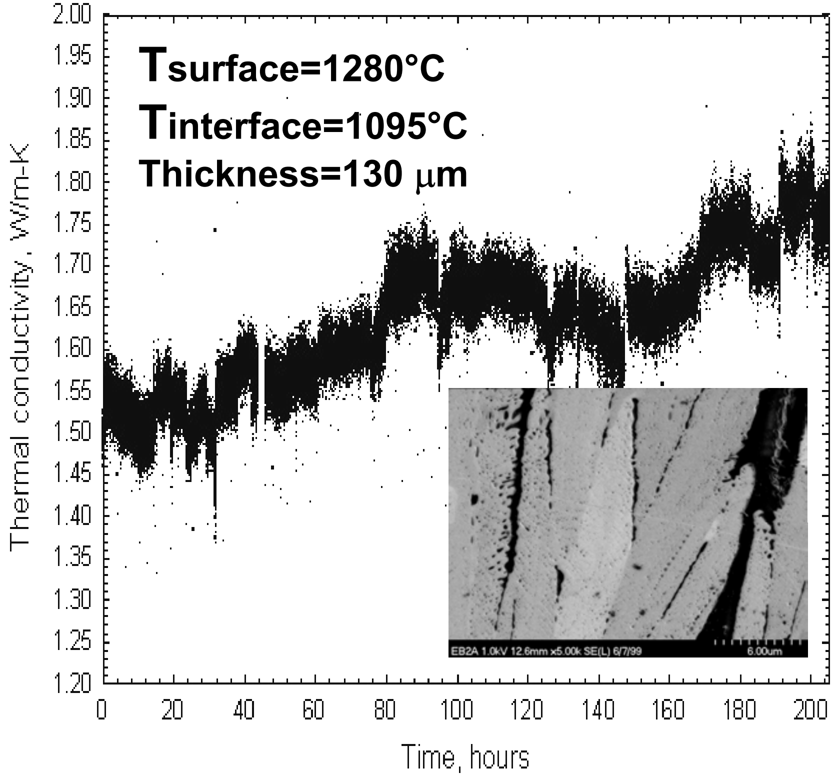
- **Approximate constant heat flux**
- **Sintering induced conductivity increase during the steady-state testing**
- **Sintered coatings tend to have accelerated delamination under subsequent cyclic testing and damage accumulation**

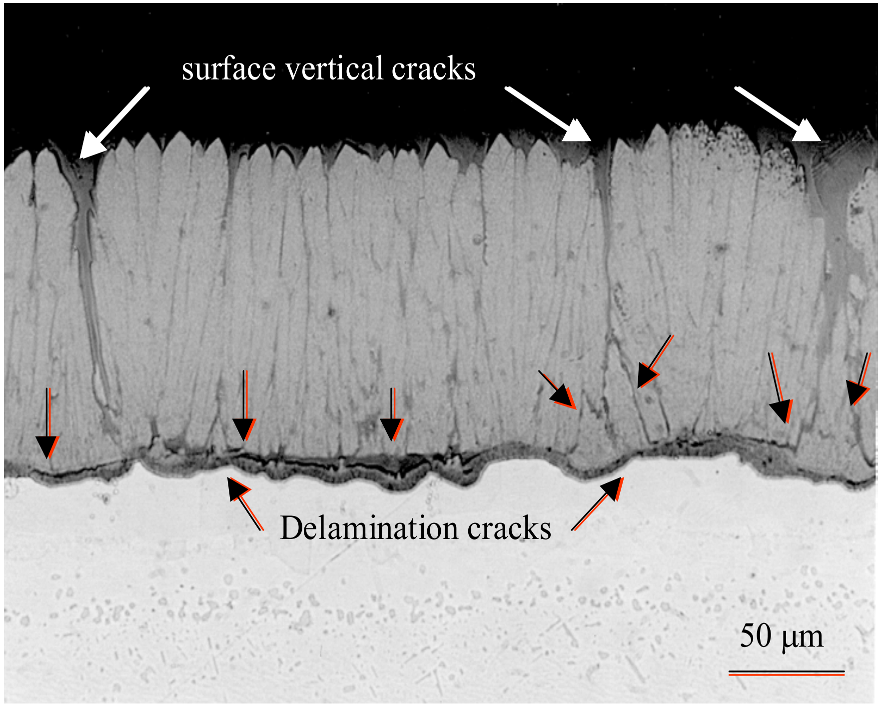




High Heat-Flux Sintering Induced Cracking and Delamination in Turbine EB-PVD ZrO_2-7wt%Y_2O_3 Coatings

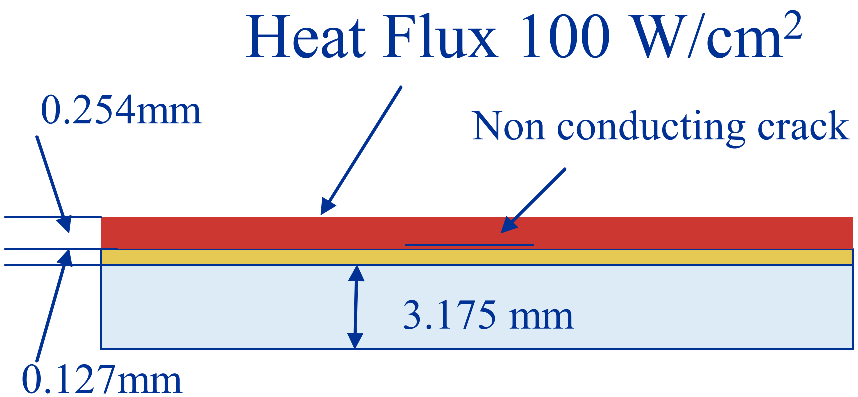
— **High-heat-flux surface sintering cracking and resulting coating delaminations**

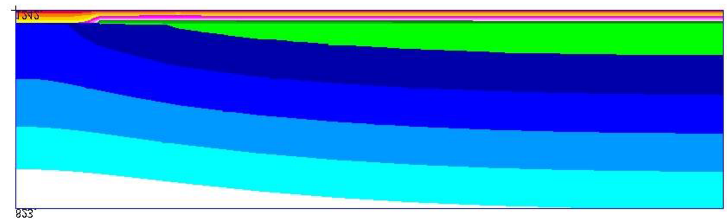


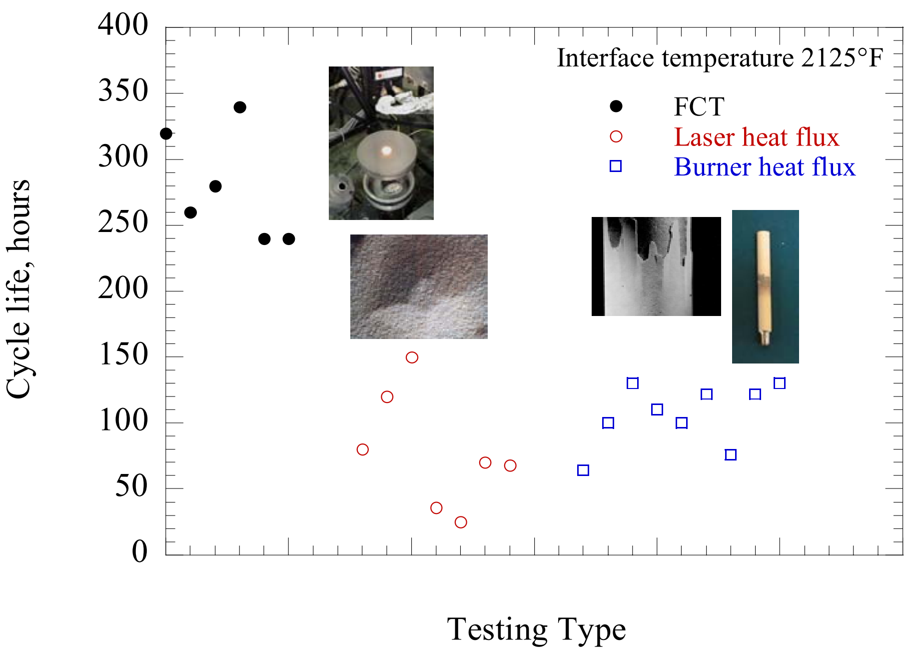


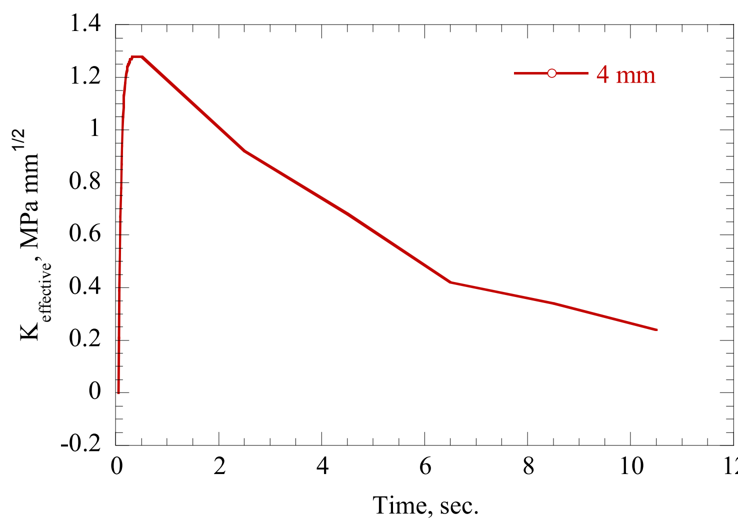
Zhu et al, Surf. Coat. Tech., Vol. 138, 2001

The Cyclic Life of Thermal Barrier Coatings

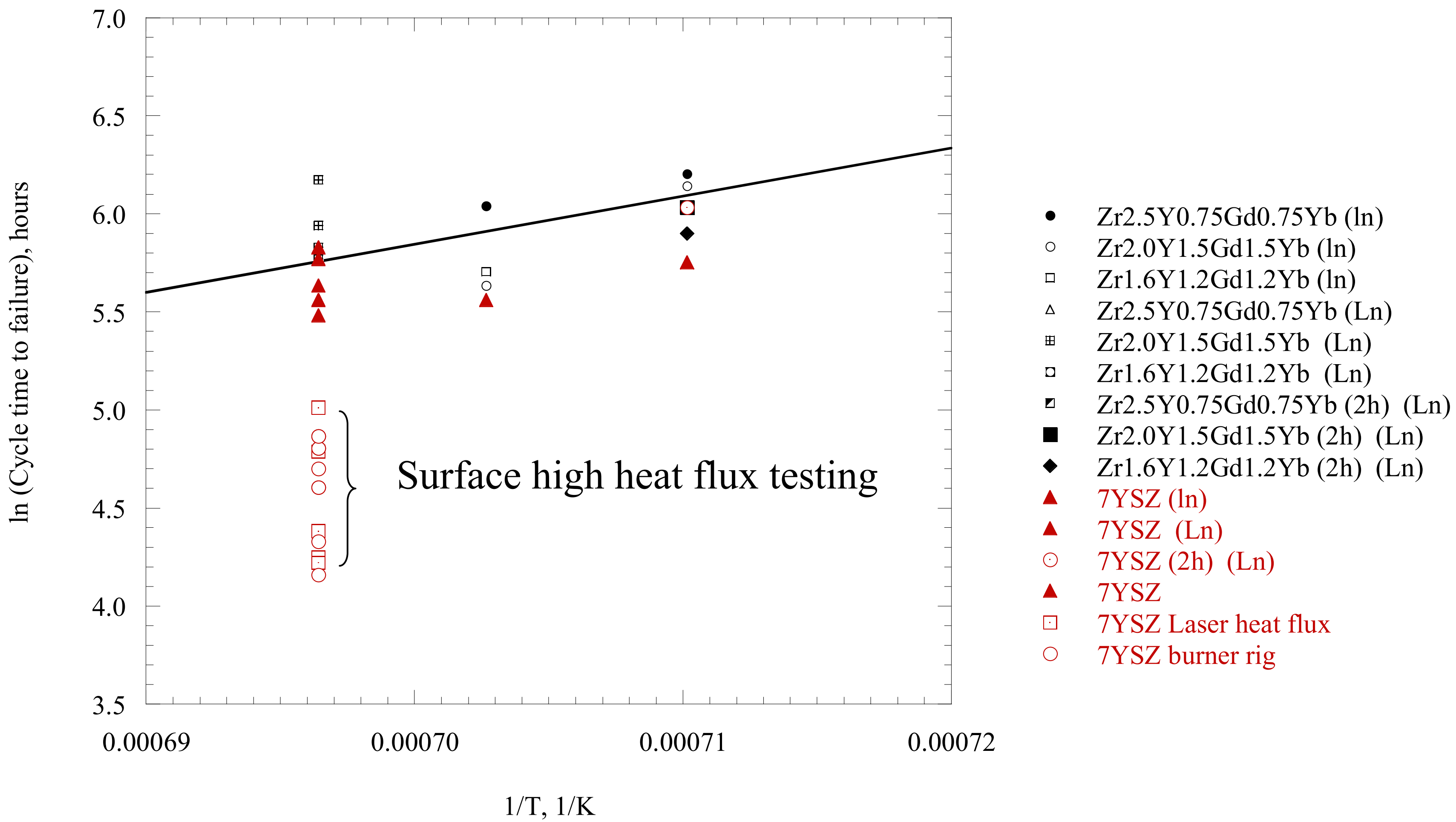






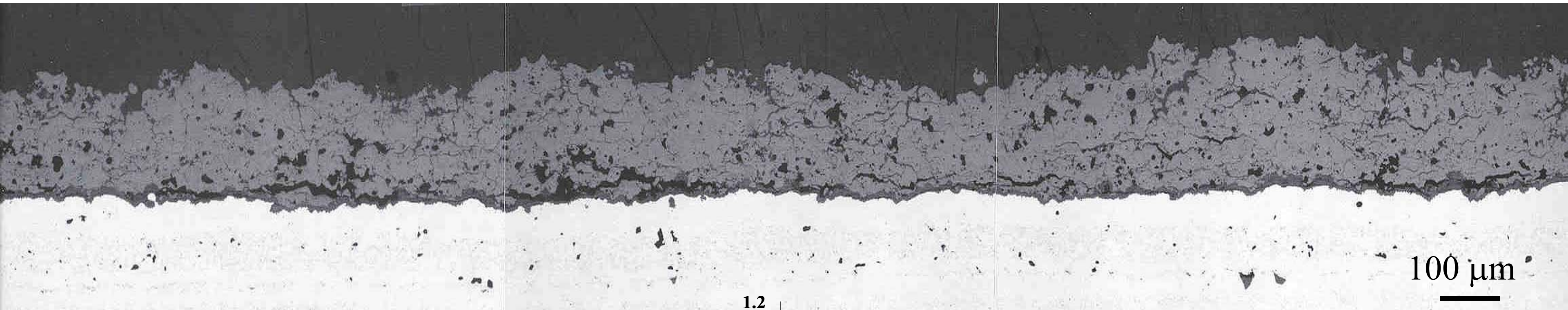


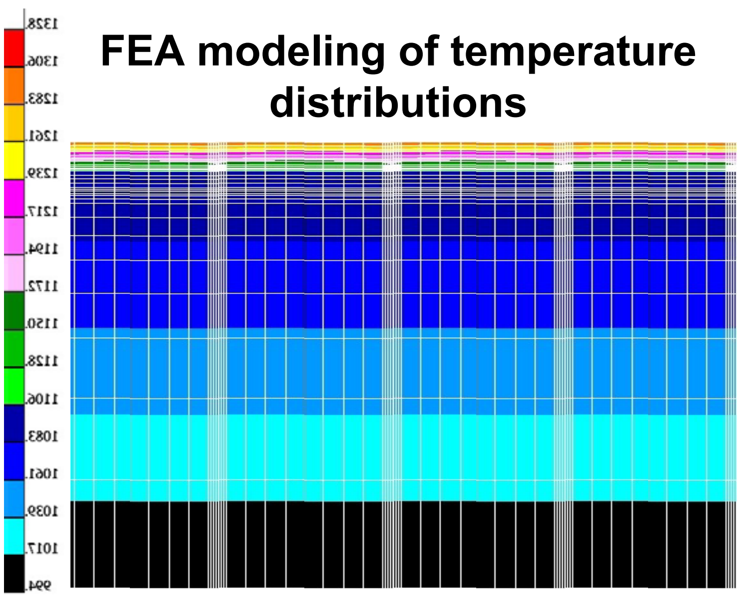
The Cyclic Life of Thermal Barrier Coatings - Continued

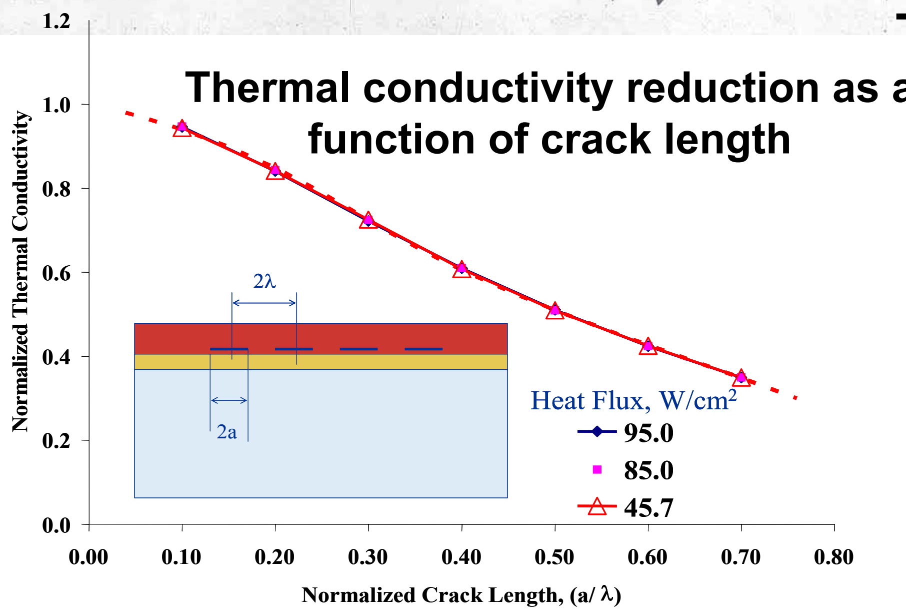


Thermal Gradient Tested TBC Delamination and Modeled TBC Delamination Induced Conductivity Reduction

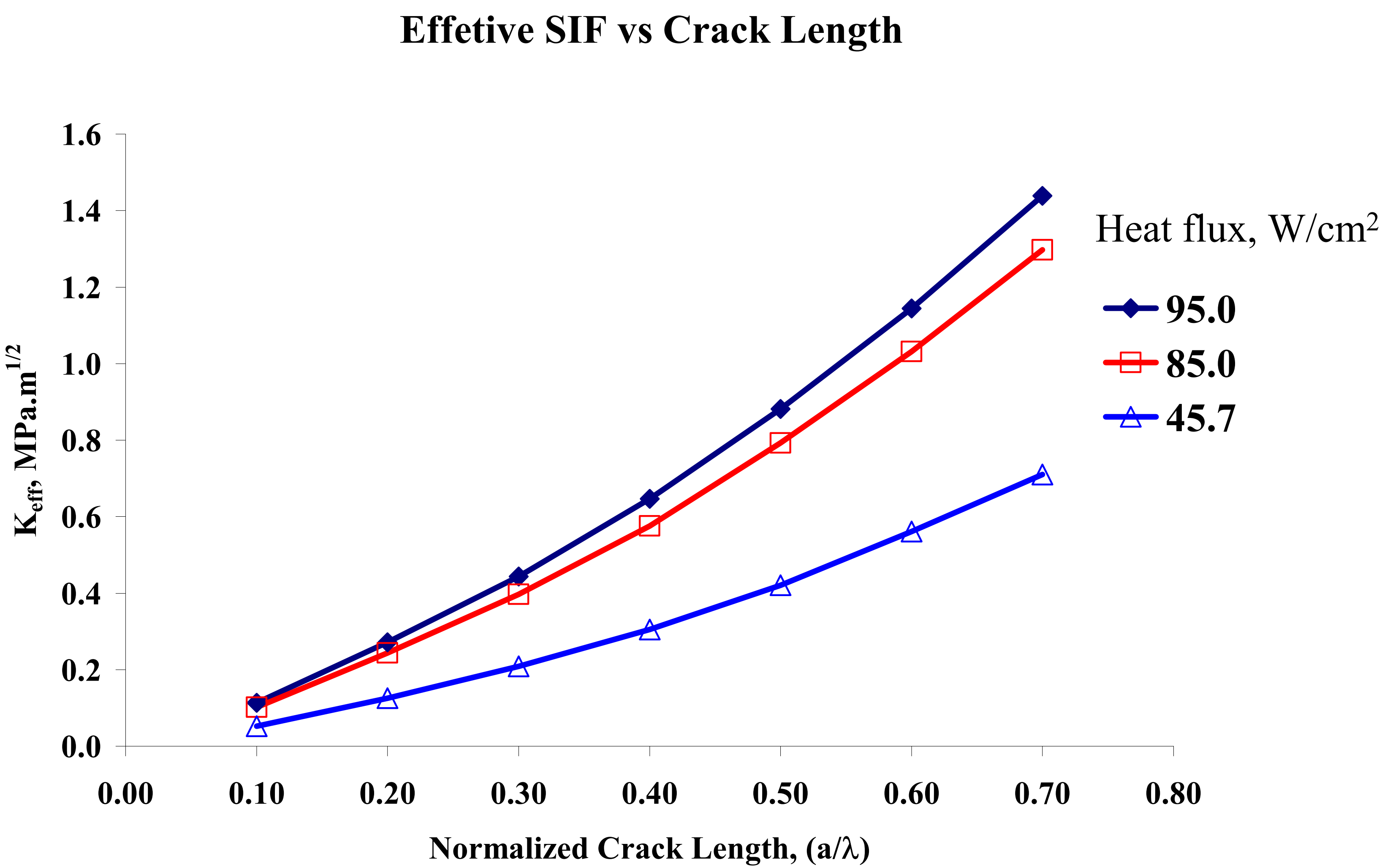
— **Laser tested at $T_{surface}$=~1316°C and $T_{interface}$=~1100°C under the combined steady state (22 hrs) and 20 min heating/3 min cooling cycles (256 cycles)**



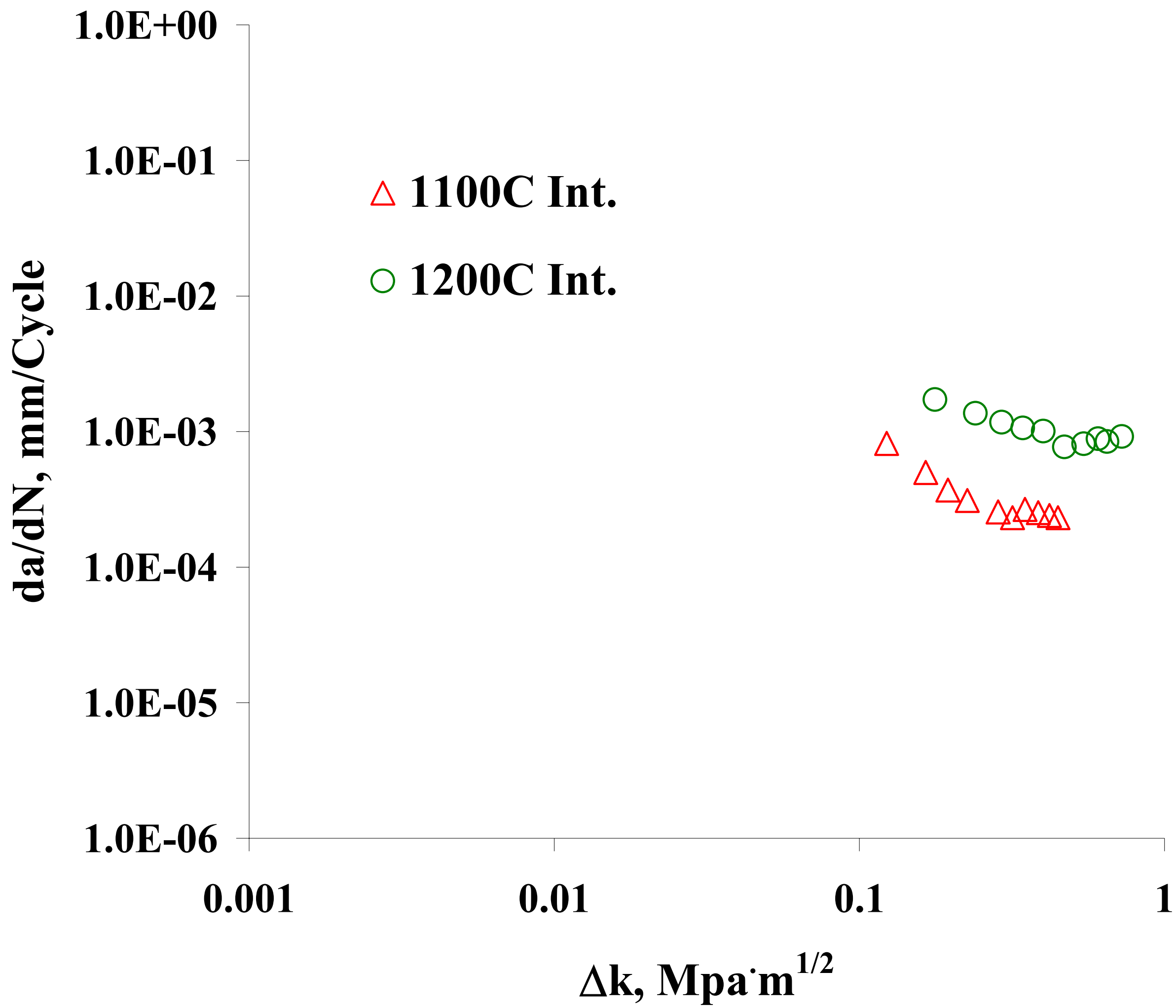




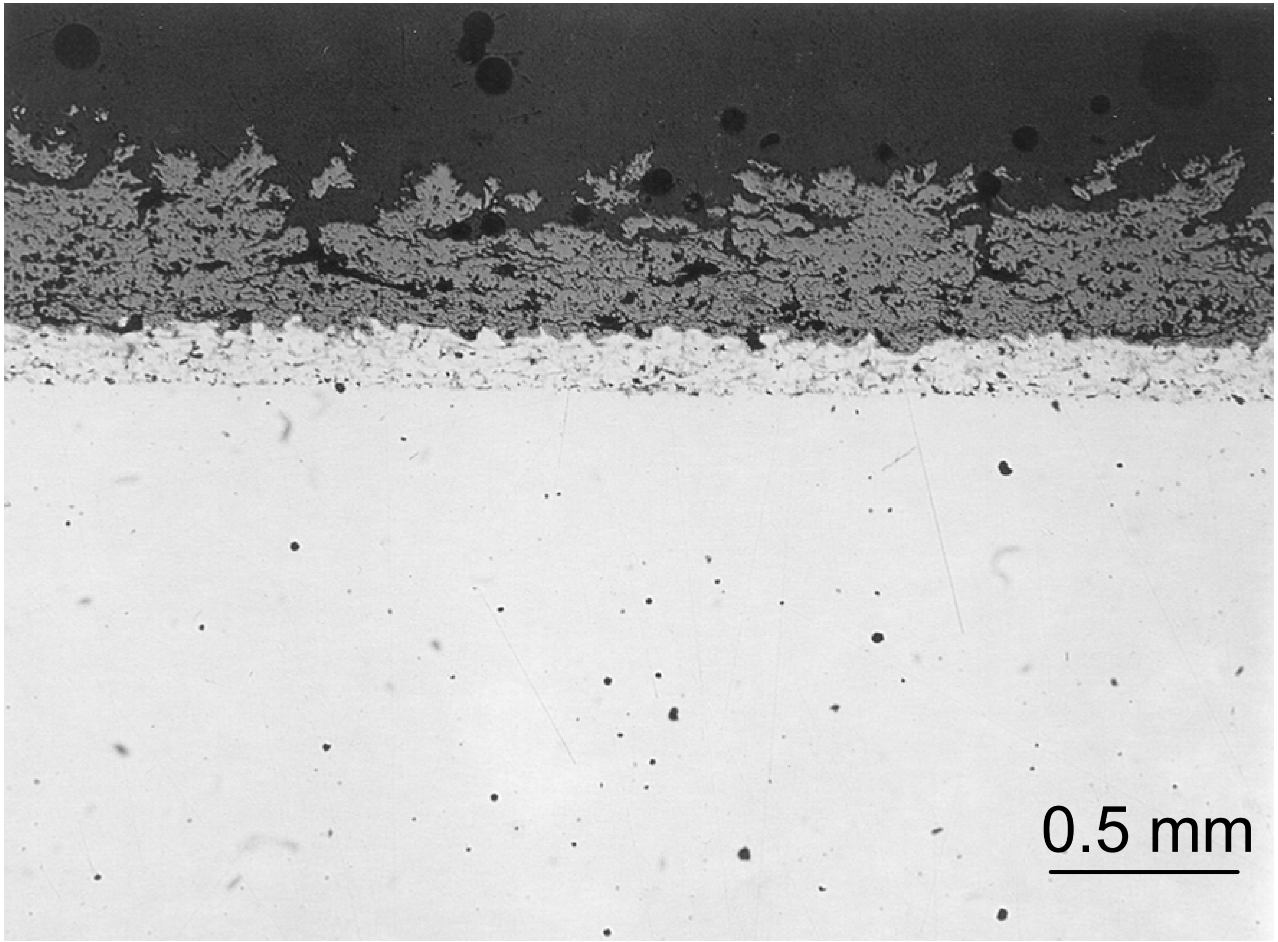
Delamination Driving Force Increases with Heat Flux



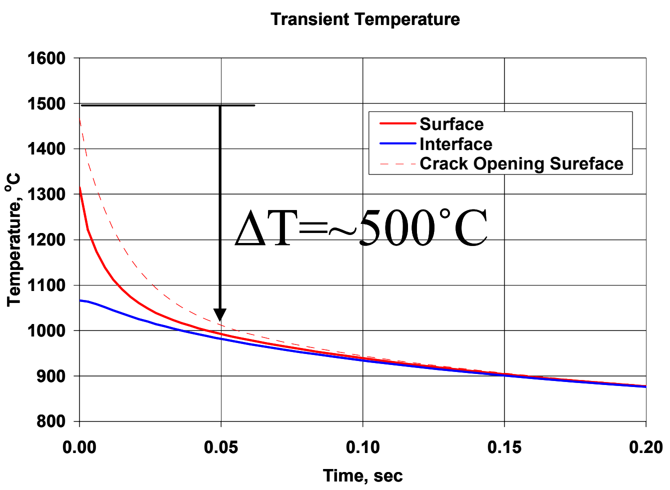
Crack Propagation Rate Increases with Interface Test Temperature

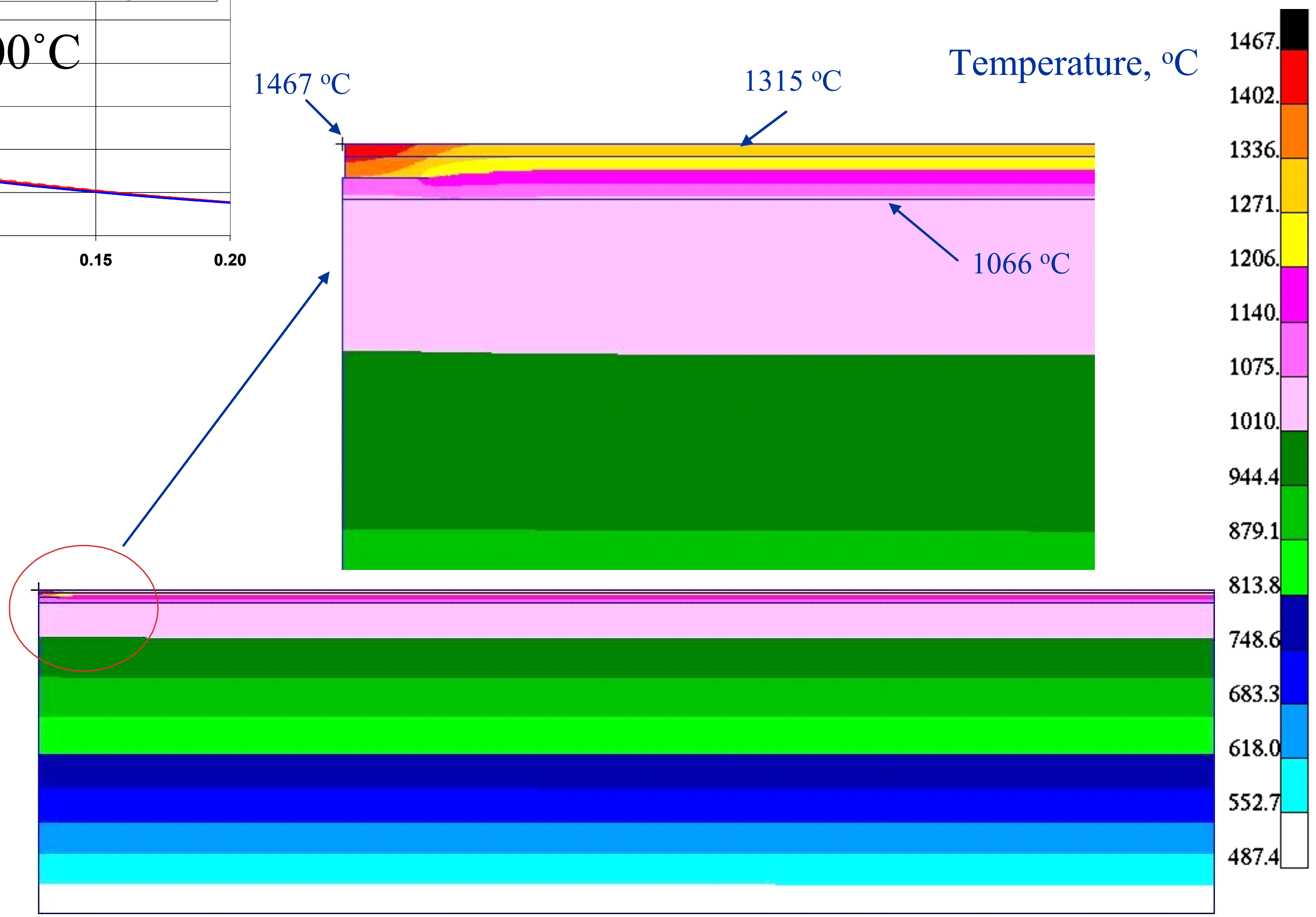


Coating Failure Modes under Very High Thermal Gradients

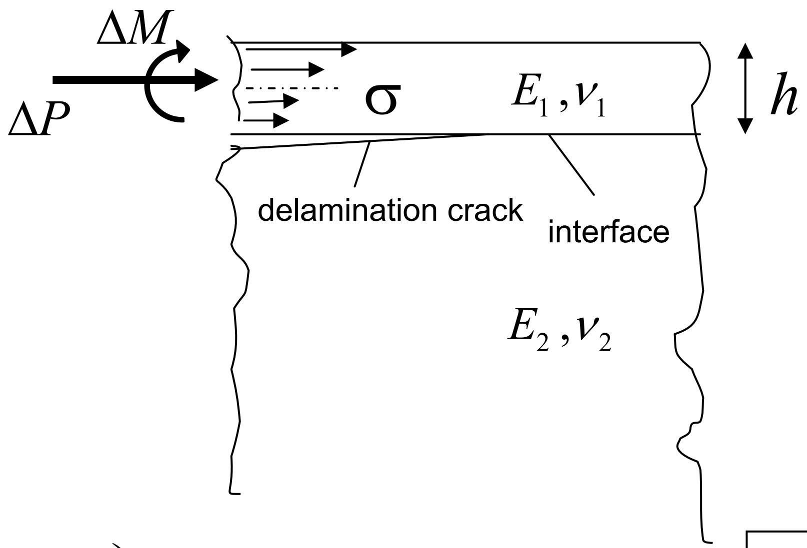


Accelerated Delamination under Vertical Surface Cracks





Delamination Driving Forces Correlated to Temperature Gradients and Coating Elastic Modulus



$$G = \frac{1}{6}\left(\frac{1+\nu_1}{1-\nu_1}\right) E_1 h \left(\alpha_1 \left(T_S - T_0\right)\right)^2$$

As compared to CTE mismatch

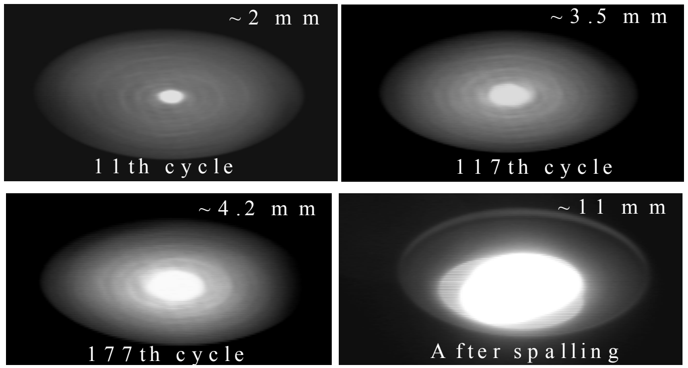
$$G = \sigma^2 h / 2\bar{E}$$
$$= [Eh(1+\nu)/(1-\nu)](\Delta\alpha\Delta T)^2 / 2$$

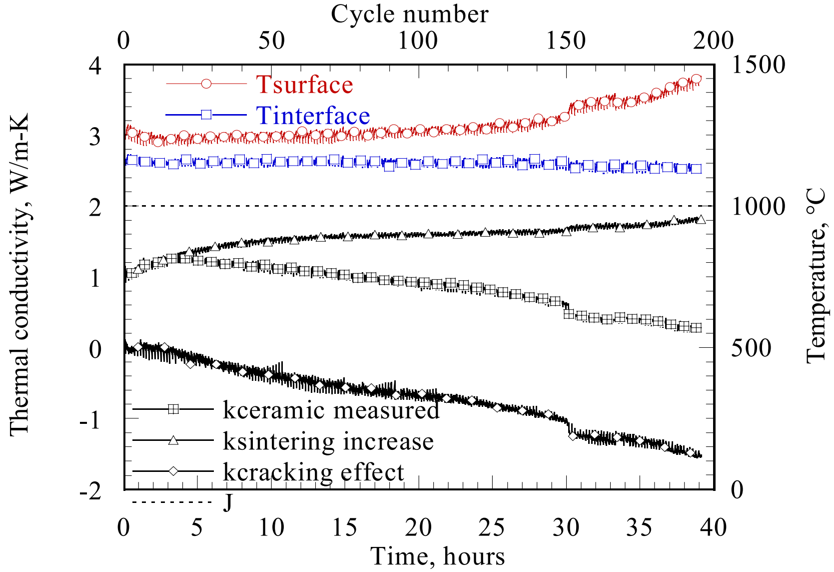
Hutchinson, Irsee, Germany 2007;
Evans and Hutchinson, Surface Coating Technology, 2007

Predicted delamination driving force G can be in the range of 20-80 J/m^2

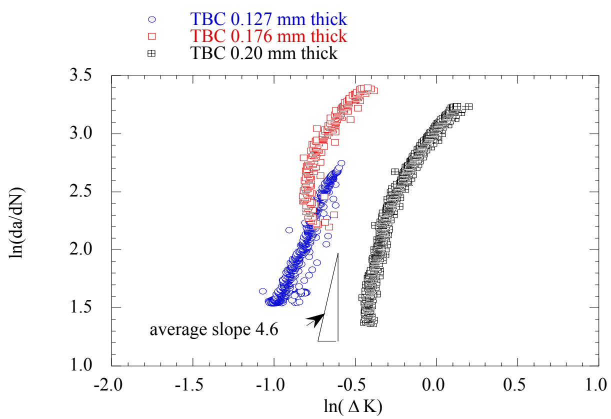
Delamination Crack Propagation Observed under Heat-Flux Thermal Gradient Cyclic Condition

A center penny-shape crack propagation





Thermal conductivity change as a function of cycle number



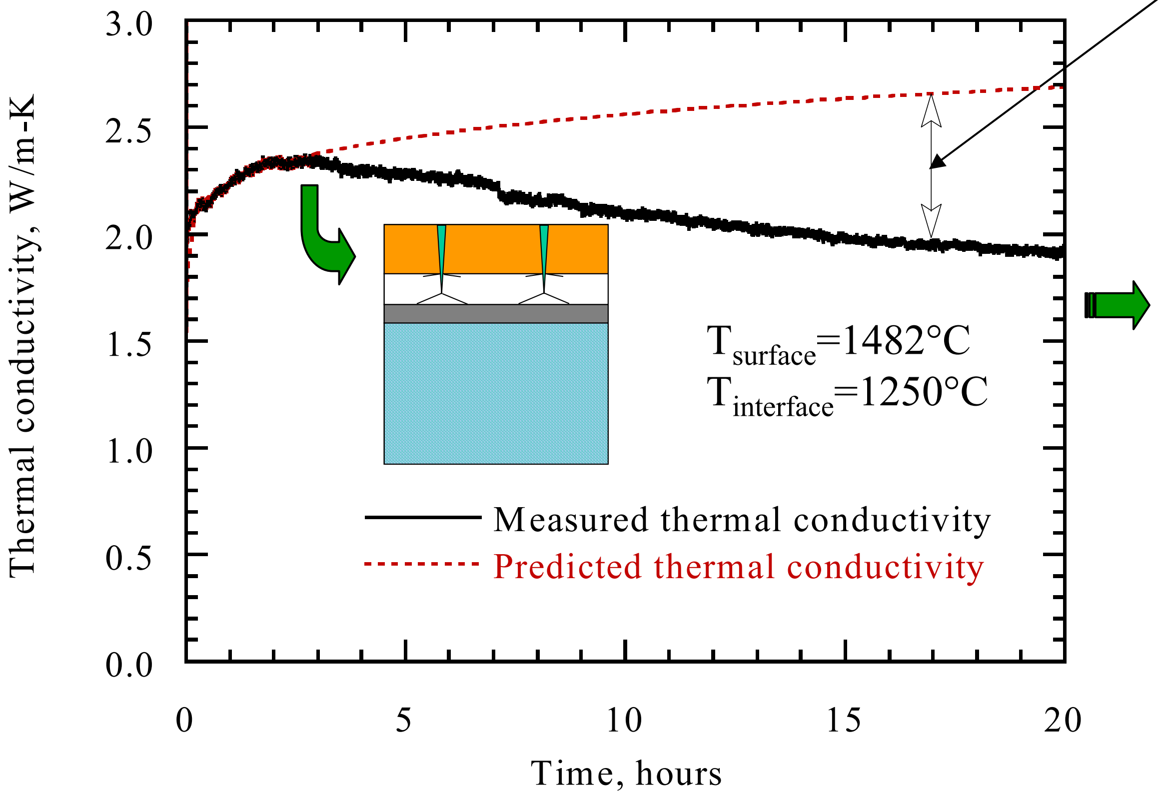
Crack propagation da/dN-stress intensity amplitude ΔK plot for life prediction

High Temperature Sintering Accelerates Cracking in Thermal and Environmental Barrier Coatings

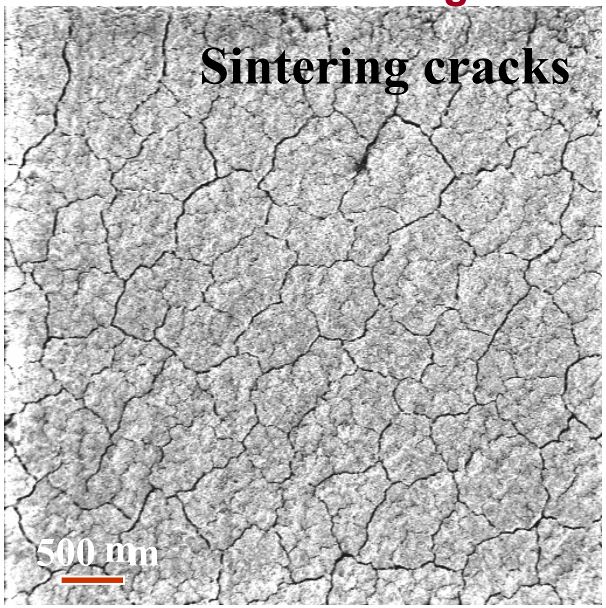
— Conductivity initially increased due to sintering

— Conductivity later decreased due to coating delamination cracking resulting from the large sintering shrinkage

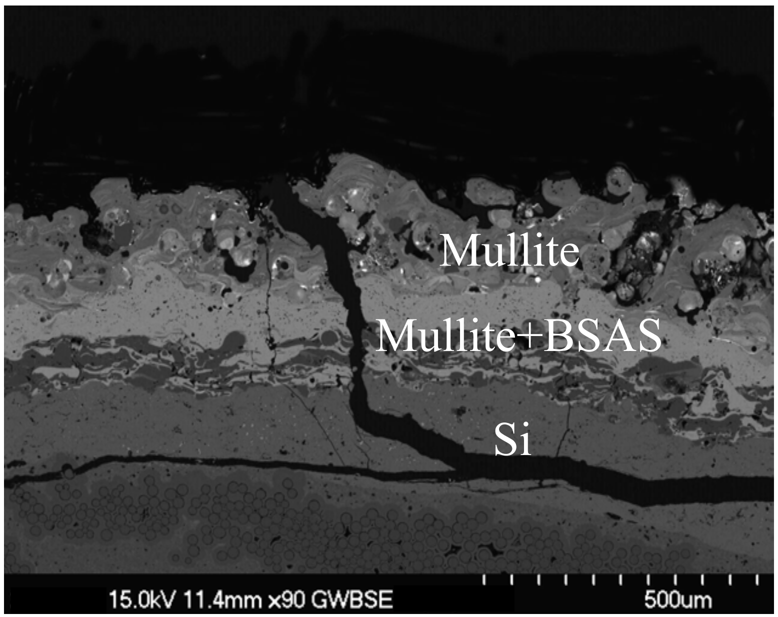
* Coating delaminates at temperature during the steady-state testing due to sintering

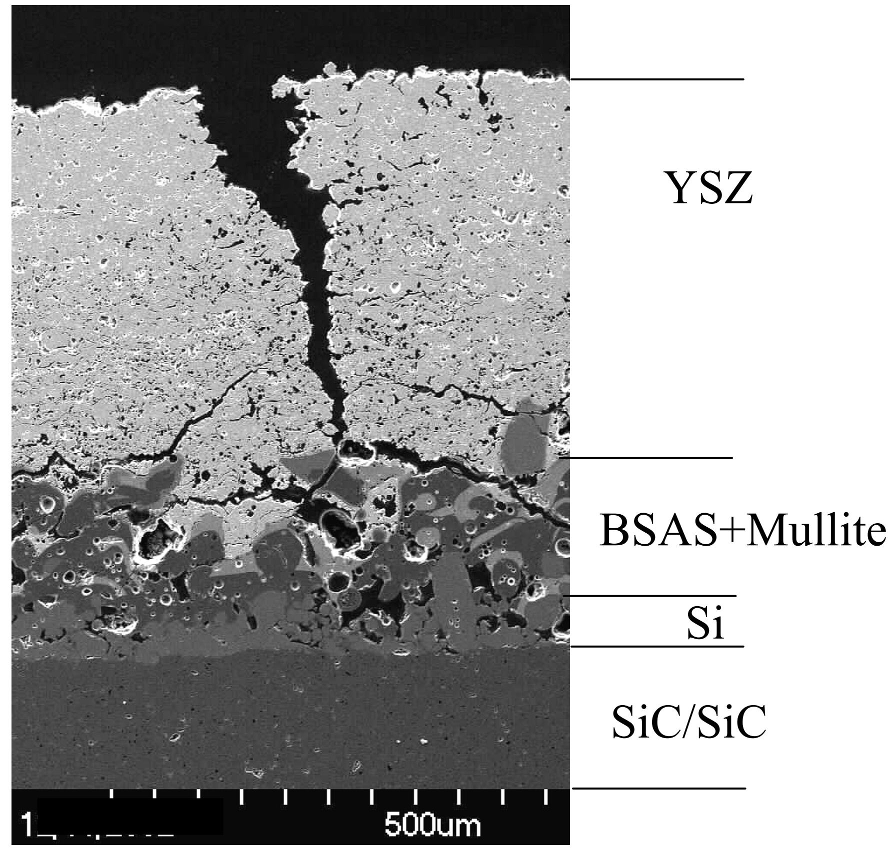


After 20h testing



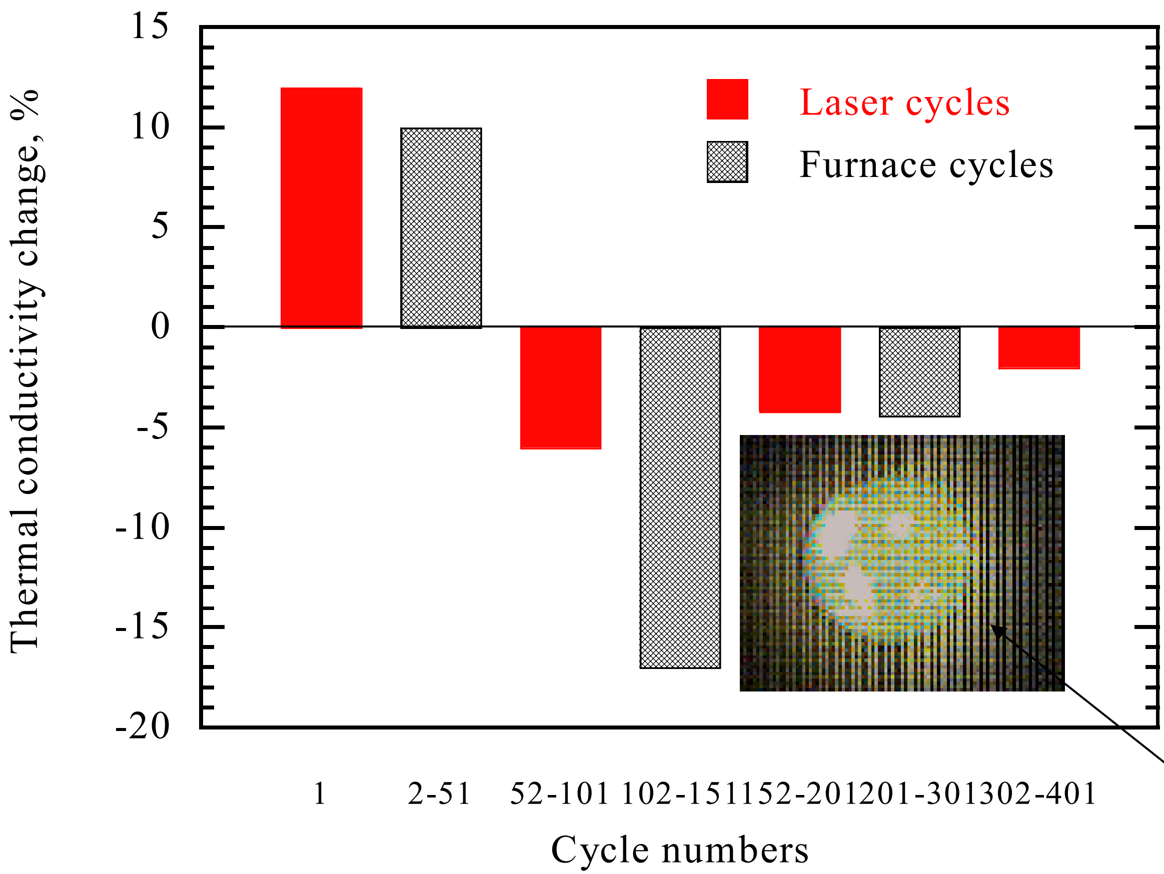
Failure Modes of Environmental Barrier Coating Systems

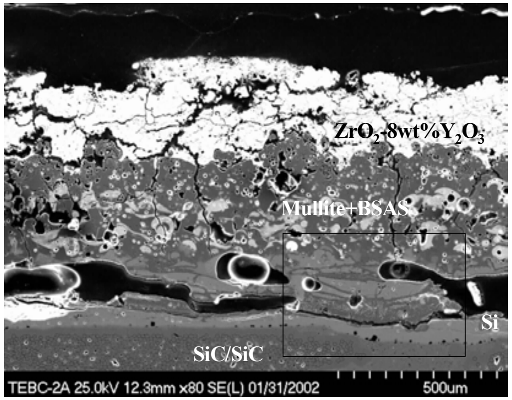


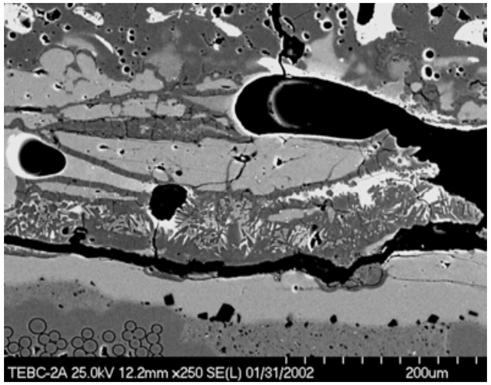


Accelerated Coating Degradation under Thermal Gradient and Water Vapor Environments

— **Significant interfacial pore and eutectic phase formation due to water vapor attack and Si diffusion at the interface temperature of 1300°C under the thermal gradient cycling conditions**

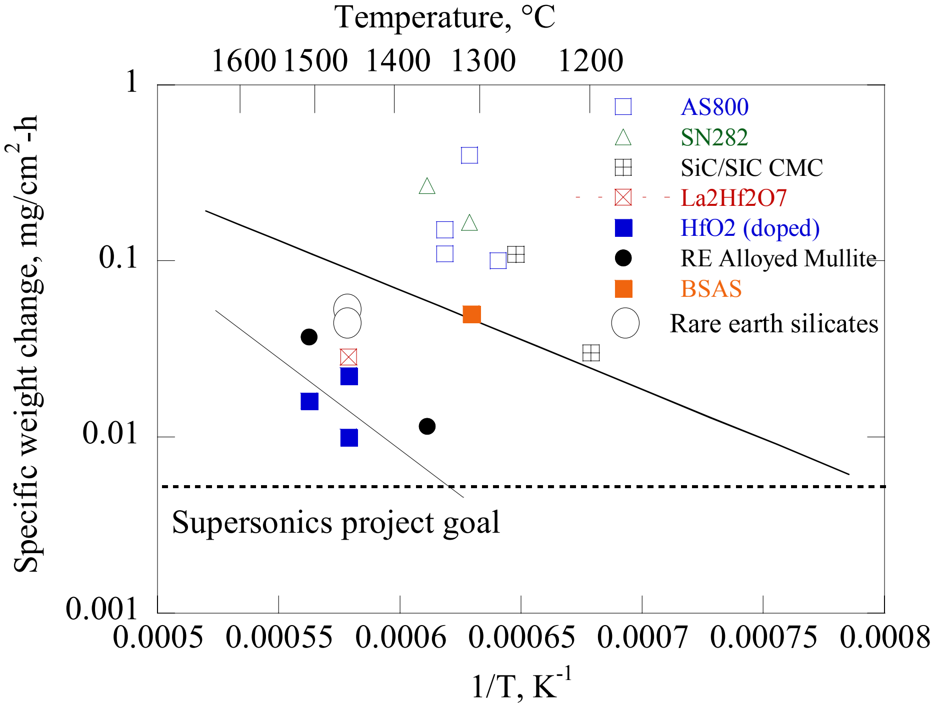


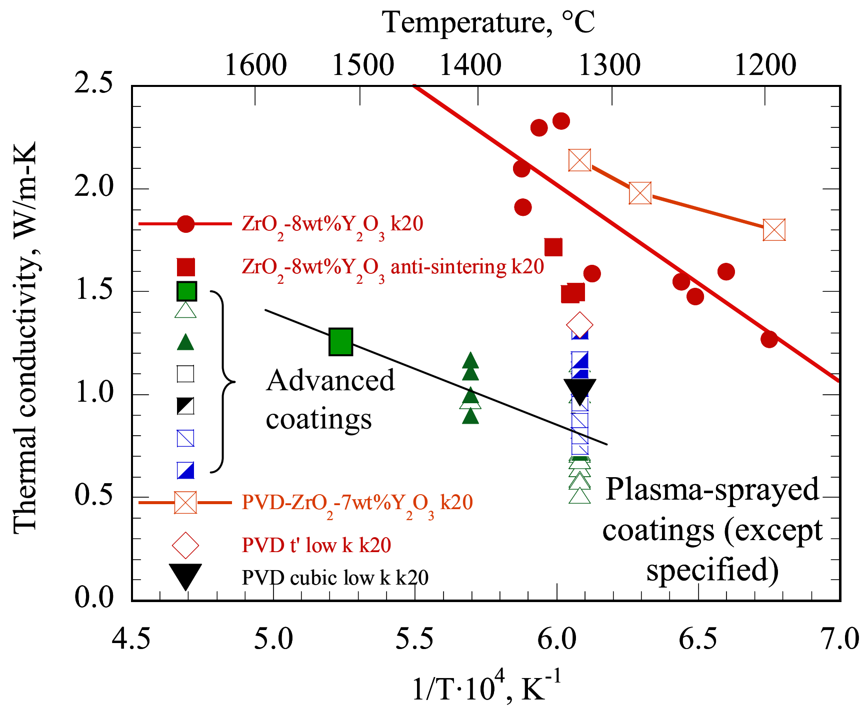




Coating spallation

Temperature Capability of Advanced Thermal and Environmental Barrier Coatings





Conclusions

- The coating failure involved both time-temperature dependent sintering and cycle dependent fatigue processes
- Coating high temperature stability demonstrated critical durability issue
- Increased delamination driving forces and accelerated degradation quantified under heat fluxes and thermal gradients
- Advanced low conductivity, high stability sintering resistant, and compliant coatings demonstrated better long-term durability
- Design databases and life prediction approaches established